AN12630

Using the FXLS8967 and FXLS8974 3-axis linear accelerometers as an inclinometer

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Document information

Information	Content
Keywords	FXLS8967, FXLS8974, Linear accelerometer, inclinometer
Abstract	This document explains how to use the FXLS8967 and FXLS8974 linear accelerometers as an inclinometer.

Revision history

Revision	Date	Description
1.1	20220426	• Global change: Revised "FXLS8964" to "FXLS8967 and FXLS8974." • Section 1: Revised third paragraph.
1	20220127	Initial release

1 Introduction

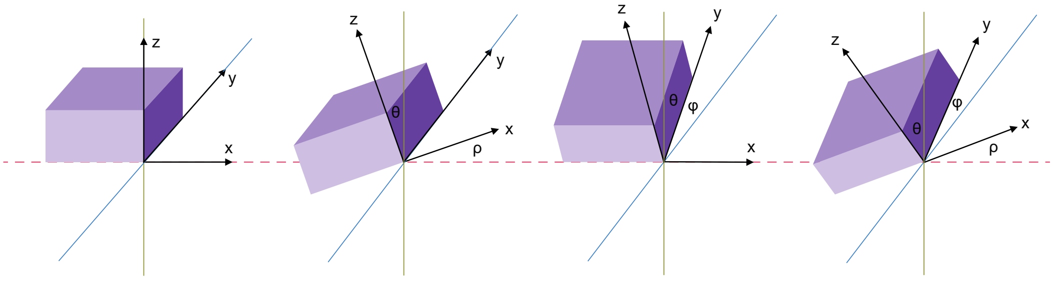
An inclinometer is a device capable of measuring precise angles (for example, tilt) of an object. One way to measure tilt angles is by using an accelerometer and local gravitational field as a reference. Accelerometers can be used to measure both static and dynamic acceleration forces. Dynamic acceleration measurement implies linear acceleration, deceleration, or vibrations for example. Tilt is considered essentially a static measurement since gravity is the only acceleration measured and used as a reference. Motion, if any, is generally at a slow rate. The underlying assumption in using an accelerometer as an inclinometer is that linear acceleration is essentially absent and that the pitch and roll angles can be measured against the rotated gravitational field vector. Therefore, the inclinometer uses the gravity vector and its projection on accelerometer axes to calculate tilt angle.

Inclination or tilt measurement has a number of useful applications in various fields. Examples include utility meter tamper detection, equipment leveling, asset tracking, orientation, combustion electricity generator tilt safety switch, and industrial motor to load alignment leveling.

This application note determines and demonstrates the accuracy of the NXP low power accelerometers such as FXLS8967 and FXLS8974, used as an inclinometer. It shows typical performance measured on two FXLS8967 demokits after a simple calibration procedure. Since FXLS8967 and FXLS8974 are 3-axis linear accelerometers, the procedure for calculating inclination angles from accelerometer outputs is derived for triple-axis use cases. The application note covers the recalibration procedure implemented to correct for typical thermal stresses due to printed circuit board soldering processes.

2 Triple-axis tilt angle calculation

One method to determine inclination angles with three axes is to calculate the angle for each axis with respect to the reference position individually. The reference position is the orientation in which the X and Y axes experience 0 g and Z-axis experiences 1 g. In this position, all tilt angles are zero. Consider the diagram in Figure 1.



- θ is the angle made by Z-axis with respect to gravity.
- φ is the angle made by Y-axis with respect to XY plane (0 g field)
- ρ is the angle made by X-axis with respect to XY plane (0 g field)

Figure 1. Determining inclination angles

Using basic trigonometry, the following equations are derived:

$$\rho = \sin^{-1} A_x \tag{1}$$

$$\varphi = \sin^{-1} A_y \tag{2}$$

$$\theta = \cos^{-1} A_z \tag{3}$$

From basic trigonometry, the following is known:

$$\sin^{-1} x = \tan^{-1} \frac{x}{\sqrt{1-x^2}} \tag{4}$$

$$\cos^{-1} x = \tan^{-1} \frac{\sqrt{1-x^2}}{x} \tag{5}$$

Applying Equation 4 to ρ and φ angles results in:

$$\rho = \tan^{-1} \frac{A_x}{\sqrt{1-A_x^2}} \tag{6}$$

$$\varphi = \tan^{-1} \frac{A_y}{\sqrt{1-A_y^2}} \tag{7}$$

Although the trigonometric equation manipulation is intuitive, these equations are not the best practical solution. In real-time use case, any amount of linear acceleration or sensor noise can lead to either A_x or A_y exceeding 1 *g* and the square-root then leads to an imaginary solution. Rewrite the above equations as shown by applying the constraint.

$$A_x^2 + A_y^2 + A_z^2 = 1 \ g^2 \tag{8}$$

$$\rho = \tan^{-1} \frac{A_x}{\sqrt{A_y^2 + A_z^2}} \tag{9}$$

$$\varphi = \tan^{-1} \frac{A_y}{\sqrt{A_x^2 + A_z^2}} \tag{10}$$

$$\theta = \tan^{-1}\frac{\sqrt{A_x^2+A_y^2}}{A_z} \tag{11}$$

The constraint is enforced to ensure that both numerator and denominator cannot be simultaneously zero. Therefore, avoid unstable tilt angle estimates. The above equations also produce constant sensitivity over a 360° rotation range.

The reason for switching from the simple inclination angle calculation using $\sin^{-1}x$ and $\cos^{-1}x$ to $\tan^{-1}x$ is for the improvement of tilt sensitivity and accuracy. Moreover, if angle measurement has to be done in the range of 0° to 180°, the sine function cannot provide unique solutions for angles in both quadrants.

In this application note, both roll and pitch angles are limited to the range of –90° to +90°. Roll is the angle derived due to rotation about the X-axis and therefore in this case, roll is given by φ and pitch is the angle due to rotation about the Y-axis and is given by ρ.

Therefore, if the accelerometer measurement vector is defined as A = (Ax, Ay, Az), the following equations are used to compute the orientation angles:

$$Roll\ \ \varphi = \tan^{-1}\frac{A_y}{\sqrt{A_x^2+A_z^2}} \tag{12}$$

$$Pitch\ \ \rho = \tan^{-1}\frac{A_x}{\sqrt{A_y^2+A_z^2}} \tag{13}$$

Note: *The roll and pitch angles defined by these equations do not follow the traditional Aerospace convention.*

3 Calibration

The calibration method used is a six-parameter calibration for offset and sensitivity done to correct for thermal stresses due to soldering. Refer to application note, AN4399[2]. Let the accelerometer outputs normalized to the units of g be A_x, A_y and A_z. Let the gain or the sensitivity parameters be W_{xx}, W_{yy} and W_{zz}. Let the offset parameters be V_x, V_y and V_z. If the calibrated acceleration outputs are given by A_{xc}, A_{yc} and A_{zc}, see Equation 14:

$$\begin{pmatrix} A_{xc} \\ A_{yc} \\ A_{zc} \end{pmatrix} = \begin{pmatrix} W_{xx} & 0 & 0 \\ 0 & W_{yy} & 0 \\ 0 & 0 & W_{zz} \end{pmatrix} \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} + \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} \tag{14}$$

The board is placed in six different orientations to apply acceleration equal to +1 *g* and –1 *g* in each of the X, Y, and Z directions. The accelerometer outputs are recorded and averaged over multiple readings for the six positions and converted into g units. The six calibration parameters are then given by the following equations:

$$W_{xx} = \frac{2}{A_x[0]-A_x[1]} \tag{15}$$

$$W_{yy} = \frac{2}{A_y[2]-A_y[3]} \tag{16}$$

$$W_{zz} = \frac{2}{A_z[4]-A_z[5]} \tag{17}$$

$$V_x = \frac{-(A_x[0]+A_x[1])}{A_x[0]-A_x[1]} \tag{18}$$

$$V_y = \frac{-(A_y[2]+A_y[3])}{A_y[2]-A_y[3]} \tag{19}$$

$$V_z = \frac{-(A_z[4]+A_z[5])}{A_z[4]-A_z[5]} \tag{20}$$

The numbers 0 to 5 denote the different orientations. In the first measurement, denoted by 0, only the X-value is taken, and the other values are not used. Similarly, in the last orientation, denoted by 5, only Z-value is considered, and X and Y values are not used.

Parameter	Acceleration
$A_x[0]$	X = +1 *g*
$A_x[1]$	X = –1 *g*
$A_y[2]$	Y = +1 *g*
$A_y[3]$	Y = –1 *g*
$A_z[4]$	Z = +1 *g*
$A_z[5]$	Z = –1 *g*

Using the above parameters, the calibrated accelerometer outputs can be obtained which in turn can be used to calculate roll and pitch angles.

The other method of calibration that can be used is the auto-zero calibration method. However, in this method, a 0 *g* reference is a must. Performing this calibration in all six positions results in increased accuracy compared to the simple calibration technique which requires the values of the device to be read in one position.

The former method of recalibration imitating the factory accelerometer calibration can be used even if the orientations do not involve a 0 *g* reference. For example, two measurement orientations that result in equal gravitational field in each axis, both positive and negative can be selected and the calibrated accelerometer output can then be calculated. This is an optimum solution since it requires just two orientations to calculate six parameters. Six measurement orientations are however chosen since it is simpler to align the board in the given six orientations than in the two orientations with equal gravitational field. The drawback of six measurement orientations is that eighteen measurements are obtained of which only six are used. Thus, the ease of alignment of the board trades off with the number of measurements that are taken and used.

Both the above mentioned calibration methods for six measurement orientations have been assessed in terms of flash and SRAM memory usage. Since the number of computations in the auto-zero calibration method might be more and might use more variables than the other calibration method, its memory usage is found to be 20 % more, comparatively and so this application note mostly focuses on factory calibration method for gain and offset.

4 Results

The above mentioned tilt angle calculation and calibration procedures were implemented on FXLS8967 shield board paired with KL25Z MCU board. A custom 2-axis Tilt table (see Figure 2) was used to orient the part in different positions between +1 *g* and –1 *g* on each axis. The flip-axis table contains motor encoders with a resolution of 40,000 counts per 360 degrees. Thus, every degree has a resolution of 111.11 counts or sub 0.01° resolution.

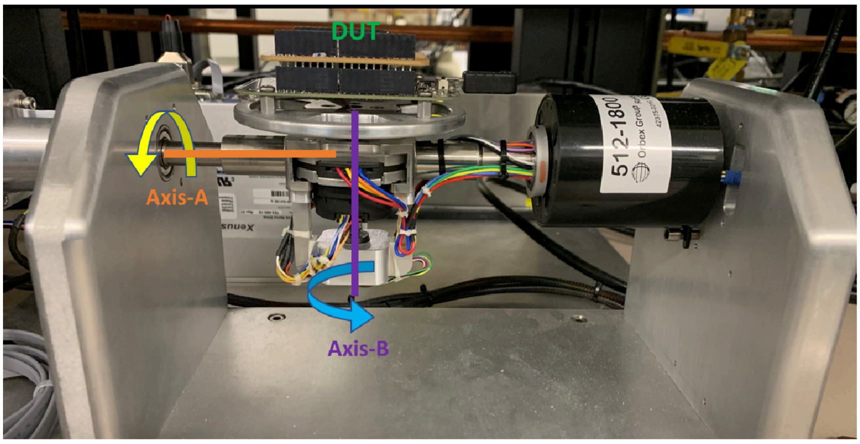


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Figure 2. Two axis tilt table

In order to avoid that the measurement table intrinsic imperfections (such as orthogonality error of its two axes and levelling error of the horizontal axis), a precision "golden" accelerometer was used to provide the reference acceleration and “true” angles. This precision accelerometer absolute accuracy in term of pitch and roll angles is typically better than 0.1°.

First, sensor calibration is performed using the six nominal orientations as described in Section 3. This initial phase provides the sensor offset and sensitivity correction coefficients that are used subsequently to improve sensor measurement accuracy as per Equation 14.

Then sensor acceleration data readings were taken when varying the table A or B angles in the range of –90° to 90° with 2° increments. All measurements have been done at room temperature.

When table roll or pitch angles are varied between –90° and 90°, the error between actual and ideal pitch angle and roll angle was calculated by subtracting the angle derived from sensor calibrated data from the precision accelerometer angle assumed to be the ideal value.

Two different devices (DUT1 and DUT2) were measured and their results are plotted in Figure 3 to Figure 6.

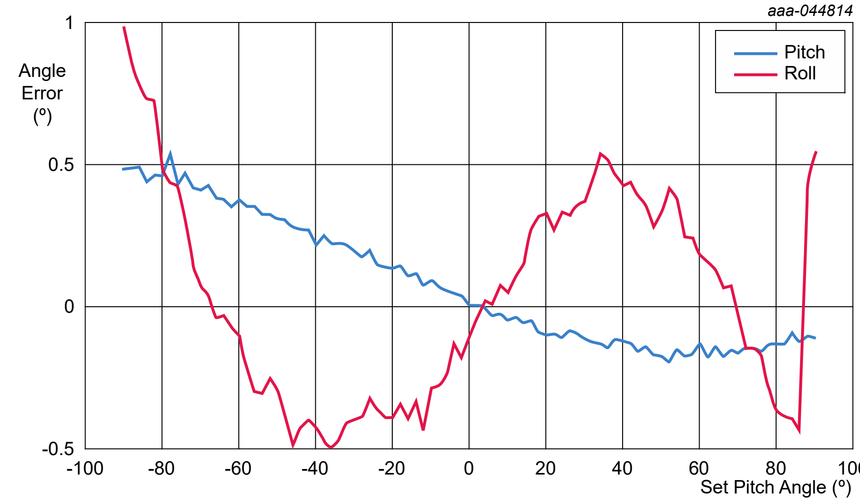

Figure 3. Plot of pitch and roll error vs pitch change for DUT1

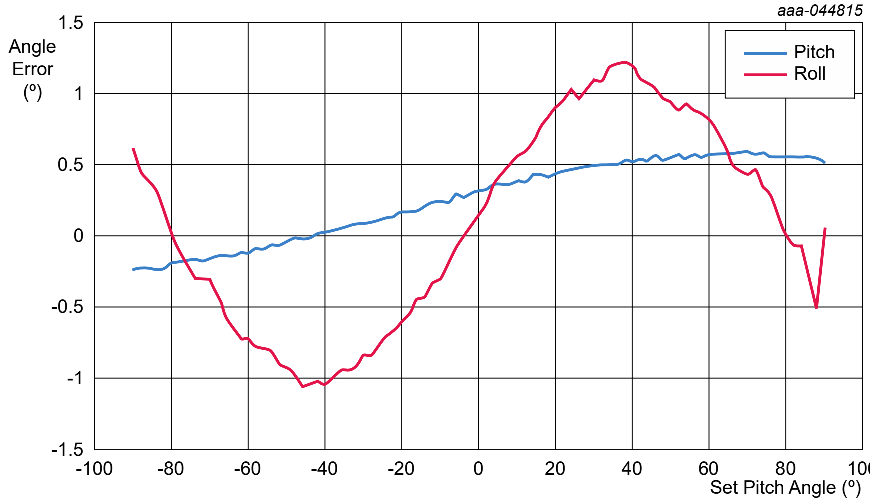

Figure 4. Plot of pitch and roll error vs pitch change for DUT2

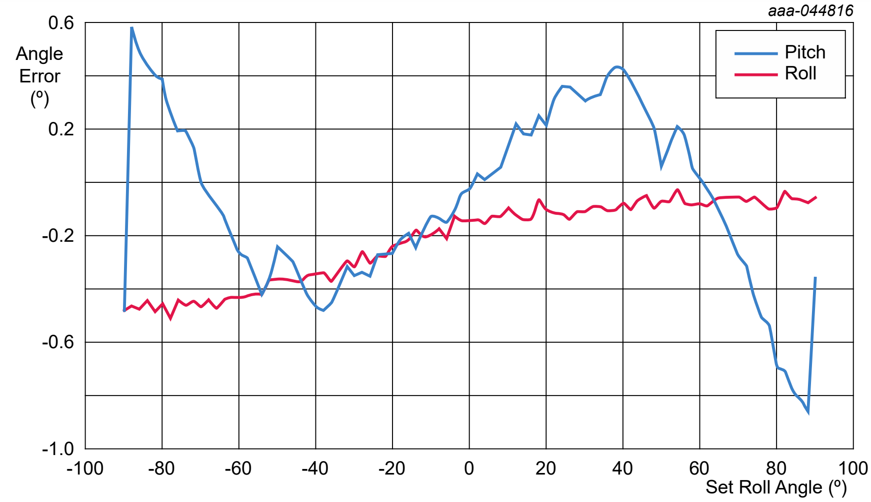

Figure 5. Plot of pitch and roll error vs roll change for DUT1

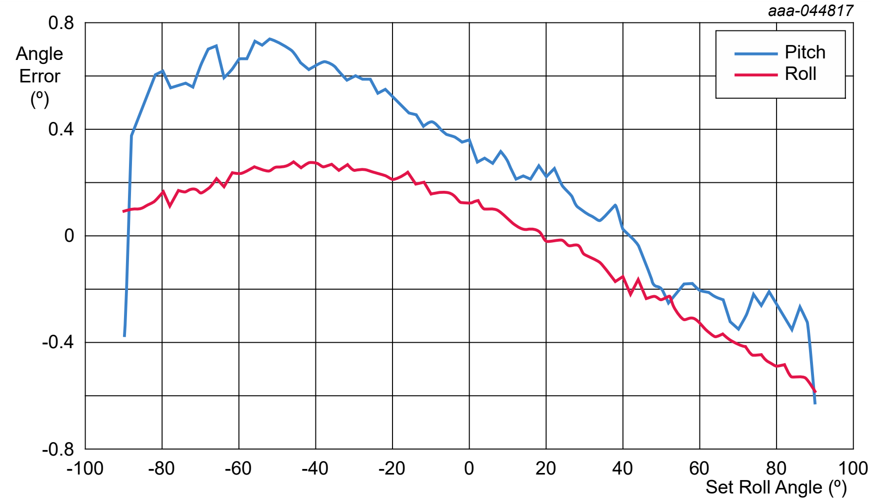

Figure 6. Plot of pitch and roll error vs roll change for DUT2

When using a simple sensitivity and offset calibration procedure, the angle accuracy measured on the two FXLS8967 accelerometer samples, is typically better than 1° as observed on the plots.

5 Summary

From the data collected using the standard 6-positions calibration method described, the FXLS8967 already provides a fair accuracy for Pitch and Roll angles, hence is suitable for generic tilt-meter or inclinometer applications.

When higher accuracy is needed, including over a wide Temperature range, more sophisticated calibration and compensation methods can be implemented such as:

- correction of the Temperature drift (TCO, TCS)
- calibration of the Sensor Cross axis sensitivity and misalignment errors

6 References

[1] AN3461 — Tilt sensing using a three-axis accelerometer
https://www.nxp.com/docs/en/application-note/AN3461.pdf

[2] AN4399 — High-precision calibration of a three-axis accelerometer
https://www.nxp.com/docs/en/application-note/AN4399.pdf

[3] AN3107 — Measuring tilt with low-g accelerometers
https://www.nxp.com/docs/en/application-note/AN3107.pdf

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